QUANTUM FLUIDS MEETS COSMOLOGY

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CONTENTS

- Bose Einstein Condensation
- Vacuum Decay
- Analogue Quantum-Fluid System
- Numerical Model
- Equilibrium Results
- Bubble Growth
- Future Plans

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- **Bose Einstein Condensation**
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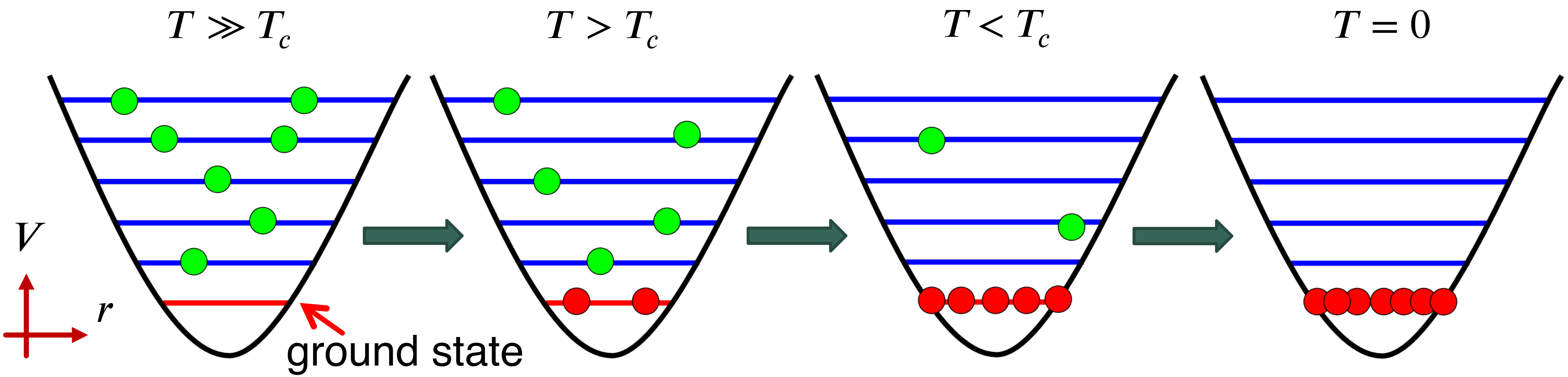
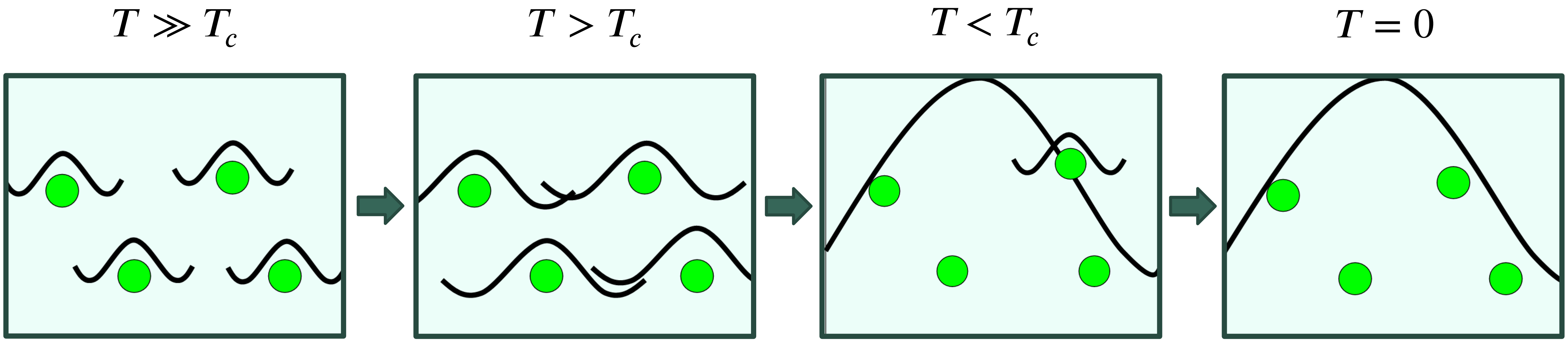
BOSE EINSTEIN CONDENSATION

- Weakly interacting gas of identical bosons
- Bosons like to occupy the same state as one another
- Below some critical temperature atoms accumulate in the ground state

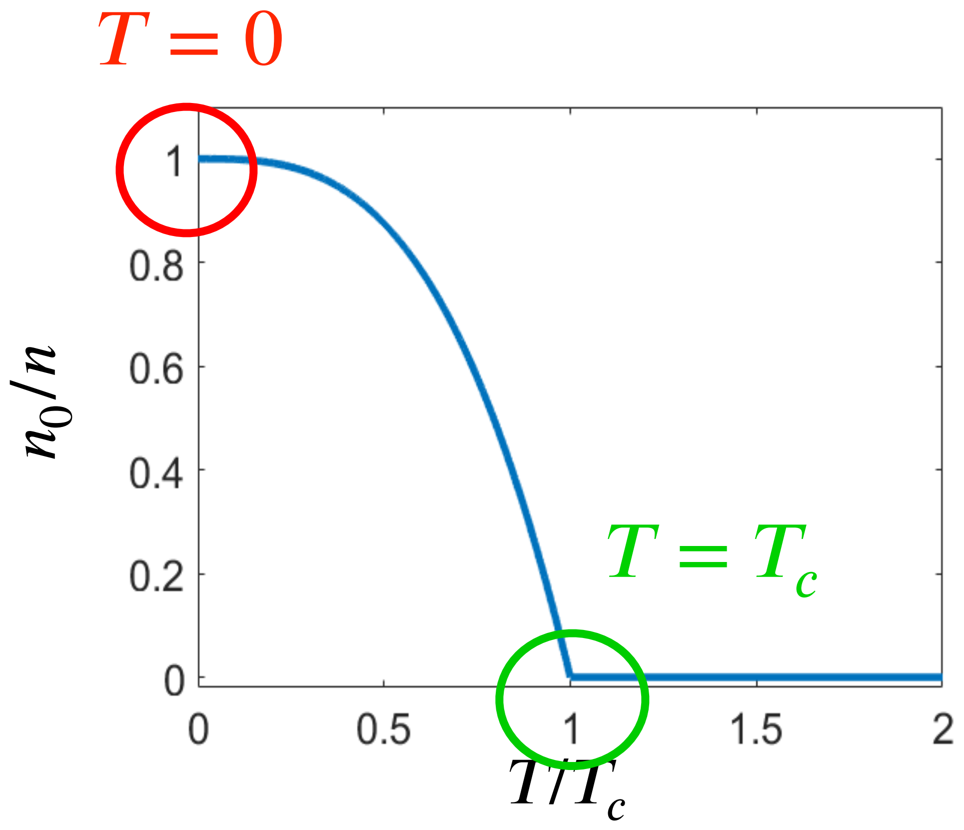


BOSE EINSTEIN CONDENSATION

- The de-Broglie wavelength: the wavelength of matter
- It gets longer as we cool
- Matter waves begin to overlap
- Bose Einstein Condensation: A collection of atoms in the ground state described by one wavefunction



BOSE EINSTEIN CONDENSATION



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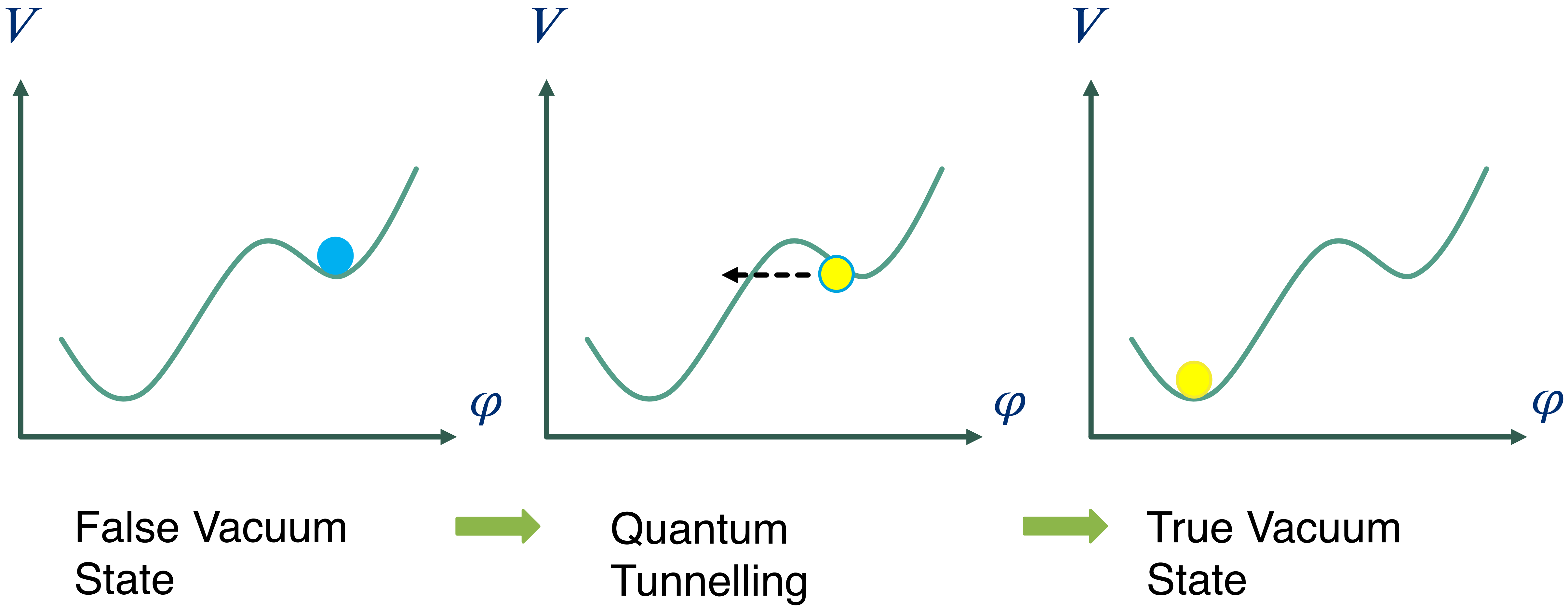
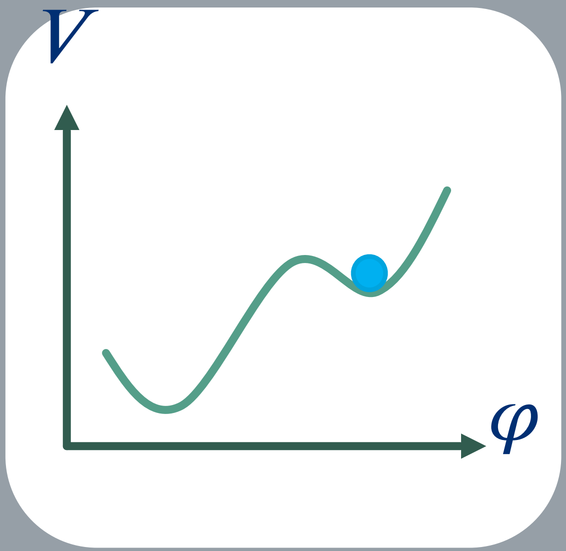
VACUUM DECAY



VACUUM DECAY – THE ELECTROWEAK PHASE TRANSITION

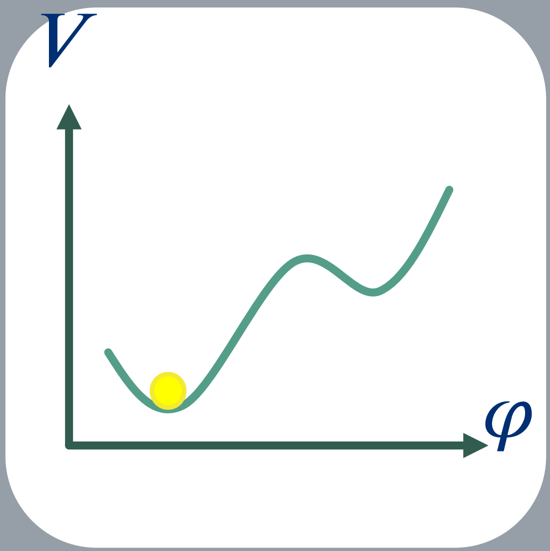
- Weak force and electromagnetic force differentiated
- Occurred ≈ 1ns after the Big Bang, $T_{\text{ew}} \approx 10^{15}\text{K}$

$T > T_{\text{ew}}$



- Higgs field in **false** vacuum
- Photons massless
- W & Z bosons **massless**
- Electromagnetic & weak forces indistinguishable

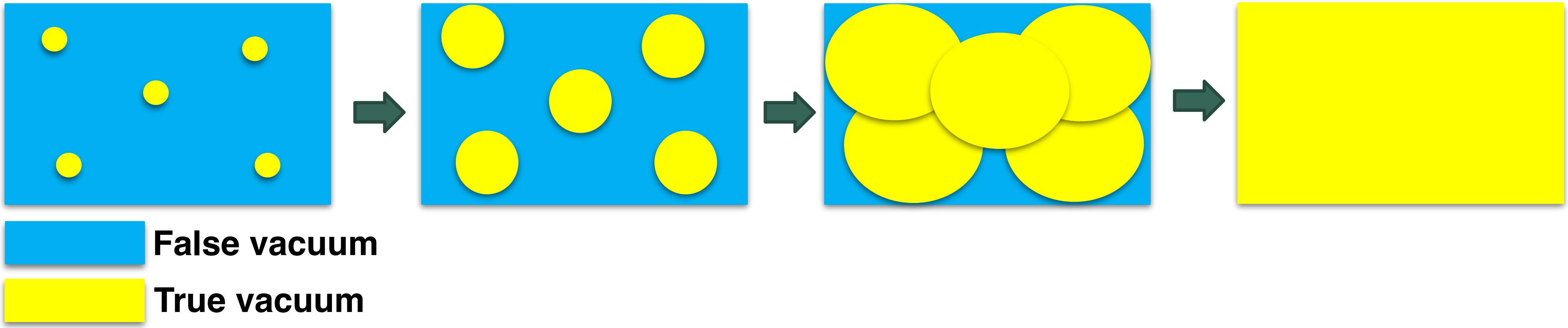
$T < T_{\text{ew}}$



- Higgs field in **true** vacuum
- Photons massless
- W & Z bosons **massive**
- Electromagnetic & weak forces distinguishable

VACUUM DECAY – THE ELECTROWEAK PHASE TRANSITION

- Standard Model: 2nd order, continuous
- Beyond the Standard Model: 1st order
- Universe converted from false vacuum to true vacuum via bubbles
- Observational consequences: baryon asymmetry, gravitational waves, magnetic fields



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ANALOGUE QUANTUM-FLUID SYSTEM

- We can model bubble growth using cold atoms
- We need a system of two components:

$$\psi_0 = \sqrt{n_0}e^{i\theta_0}, \qquad \psi_1 = \sqrt{n_1}e^{i\theta_1}$$

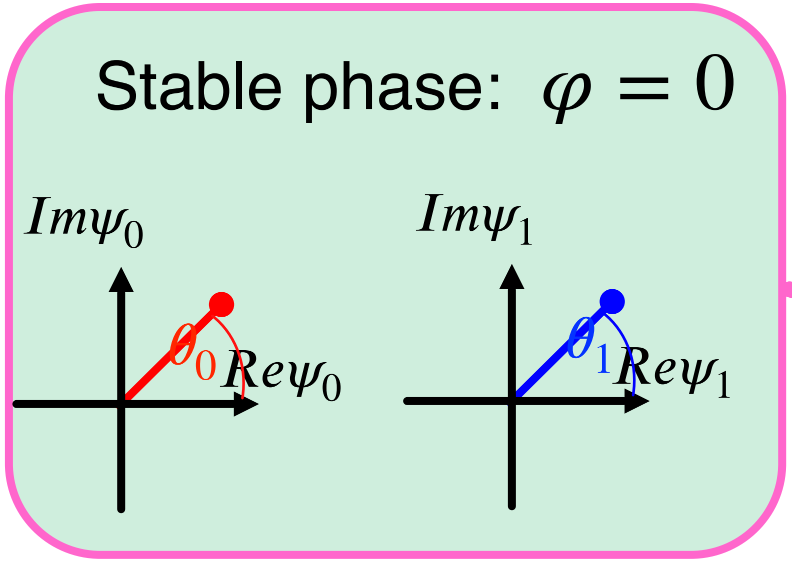
- Static interaction potential:

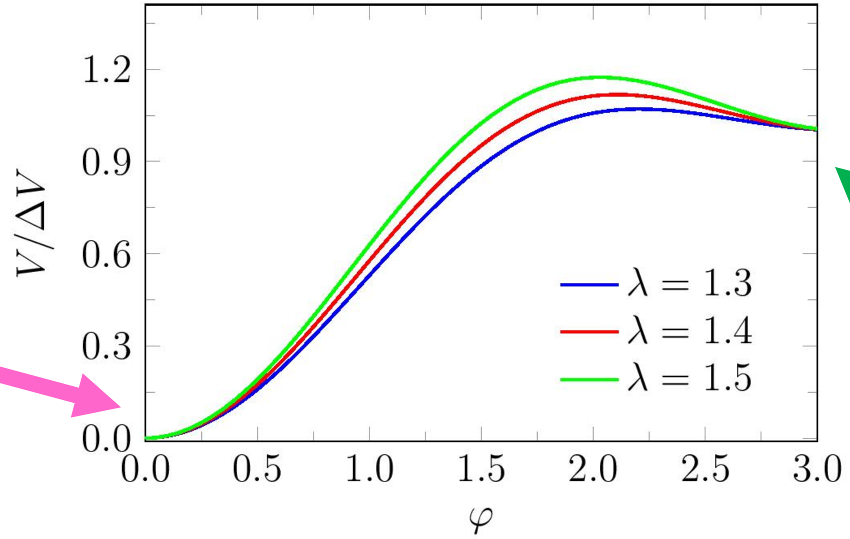
$$V = \frac{g}{2}\sum_i \left(\psi_i^*\psi_i\right)^2 - \mu\psi^*\psi - \mu\epsilon^2\psi^*\sigma_x\psi + \frac{g}{4}\lambda^2\epsilon^2\left(\psi^*\sigma_y\psi\right)^2$$

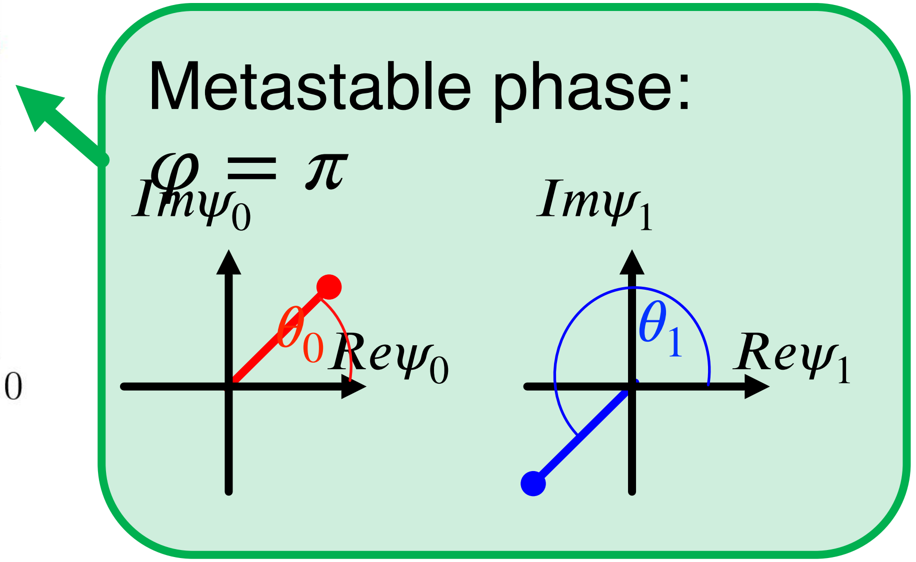
ANALOGUE QUANTUM-FLUID SYSTEM

- Scalar of interest: $\varphi = \theta_0 - \theta_1$
- Interaction potential becomes:

$$V \approx -2\epsilon^2 - 2\epsilon^2\cos(\varphi) + \epsilon^2\lambda^2\sin^2(\varphi)$$







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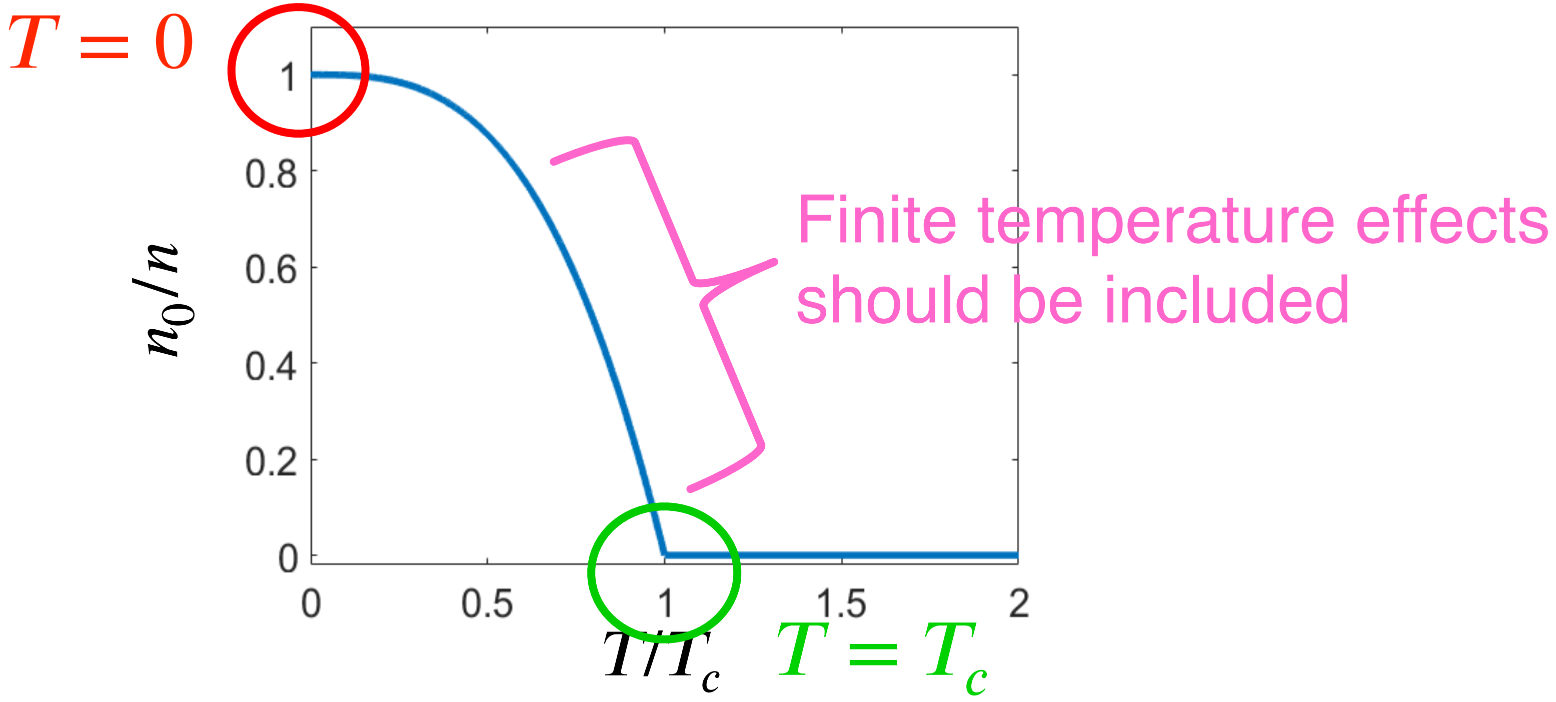
NUMERICAL MODEL

- We use a finite temperature approach
- Interested in all highly occupied, low energy modes
- Not just the ground state

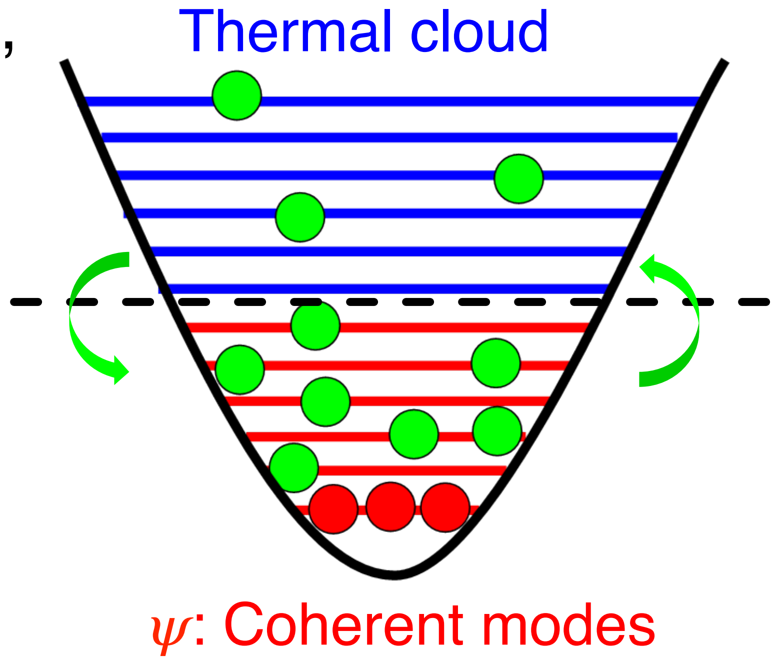


NUMERICAL MODEL

- Stochastic-Projected Gross-Pitaevskii Equation (SPGPE):
- Two coupled equations:

$$i\partial_t \psi_j = \mathcal{P}\left[(1 - i\gamma)\left\{ -\frac{1}{2}\nabla^2 \psi_j + \frac{\partial V}{\partial \psi_j^*} \right\} + \eta_j \right],$$

$$j = 0, 1$$



- ψ: Highly occupied, low momentum modes
- γ: Dissipation
- η: Gaussian noise with correlations:

$$\left\langle \eta_i(x,t)\eta_j(x',t') \right\rangle = 2\gamma T \delta(x - x')\delta(t - t')\delta_{ij}$$

- $\mathcal{P}$: Projector, eliminates high wavelength modes

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EQUILIBRIUM

- System: 1D box with periodic boundaries
- Protocol: initiate in stable “true vacuum” state and let system equilibrate.
- Temperature range: $T = 0.01 \; - 0.1$
- $\lambda = 1.4$

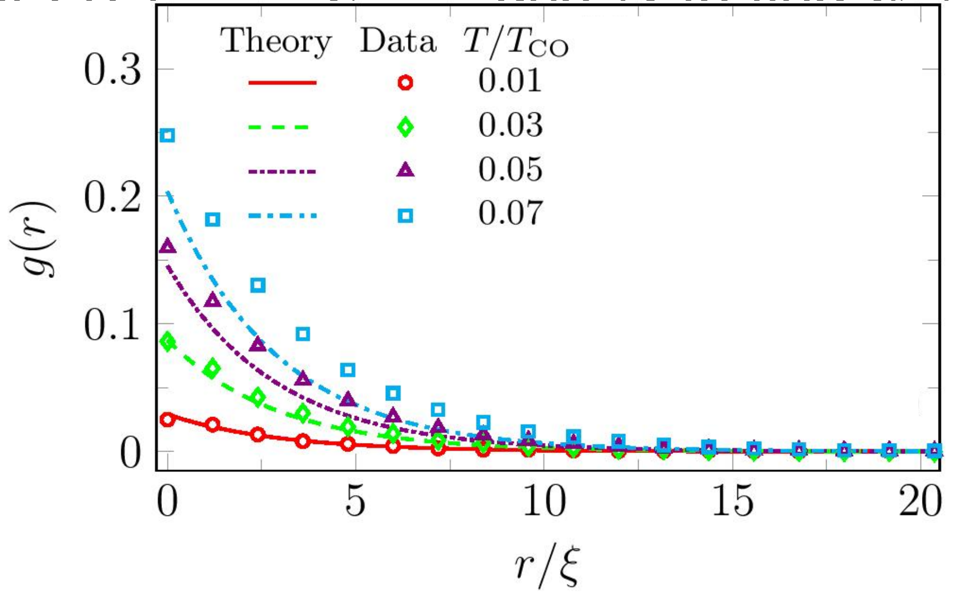
CORRELATION FUNCTION

- Consider spatial correlation function of the **phase difference φ**

  $g(r) = \langle \varphi(x)\varphi(x')\rangle - \langle \varphi(x)\rangle\langle \varphi(x')\rangle$, where $r = |x - x'|$.

- Theory: $g(r) = \frac{T}{m} e^{-mr}$, where $m(\lambda)$ is the mass of the true vacuum.

- Better agreement: Fit $g(r) = \frac{T}{m} e^{-Ar}$, use A to find λ_{cf}.



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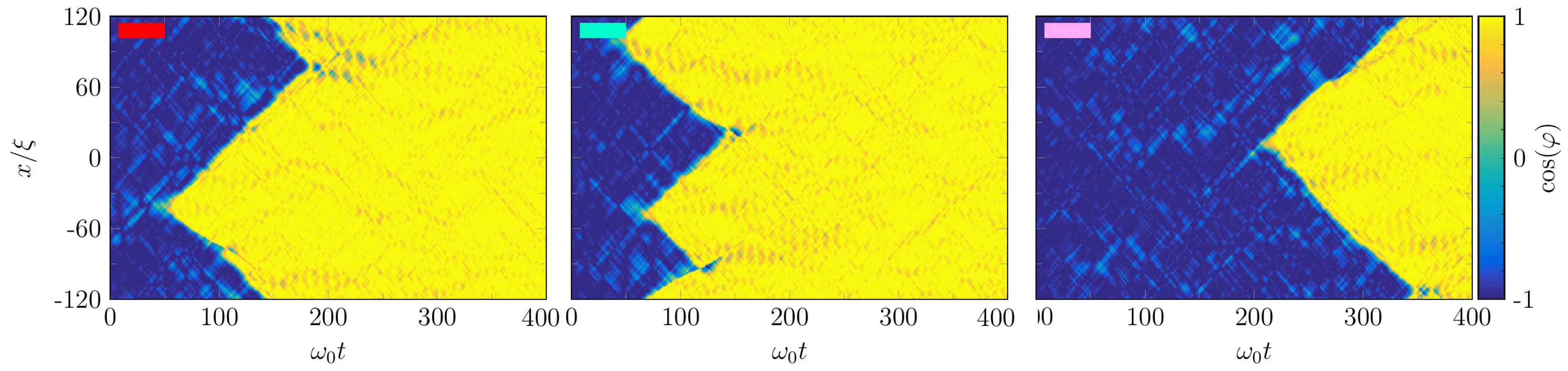
OBSERVING BUBBLES

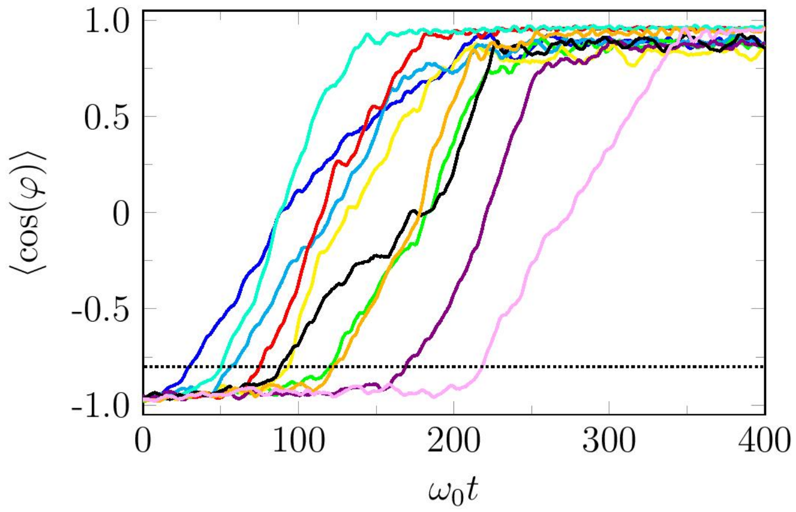
- System: 1D box with periodic boundaries
- Protocol: Initiate in metastable state and wait for bubbles to form
- Temperature range: $T = 0.015 - 0.03$

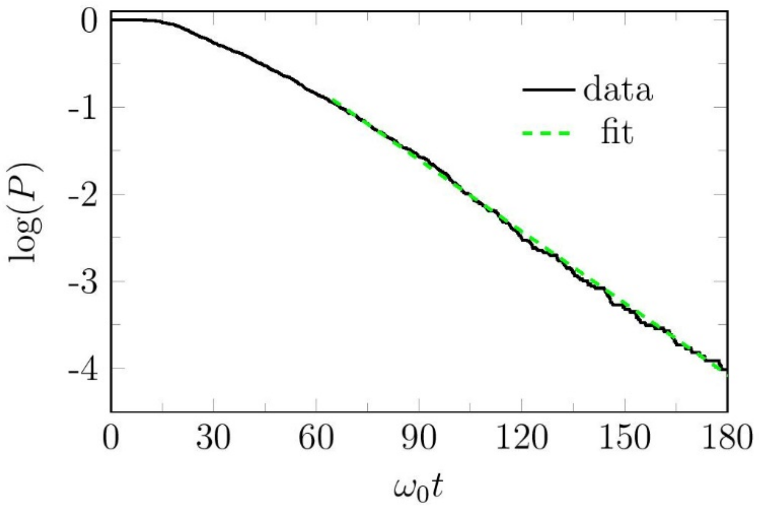


Three simulation runs at $T = 0.03$

OBSERVING BUBBLES

- We're interested in the probability, P, of remaining in the false vacuum
- Consider many trajectories of $\langle \cos(\varphi) \rangle$
- We say a bubble has formed when $\langle \cos(\varphi) \rangle$ reaches -0.8.
- $P(\mathrm{t})$: The proportion of trajectories for which $\langle \cos(\varphi) \rangle < -0.8$
- First or





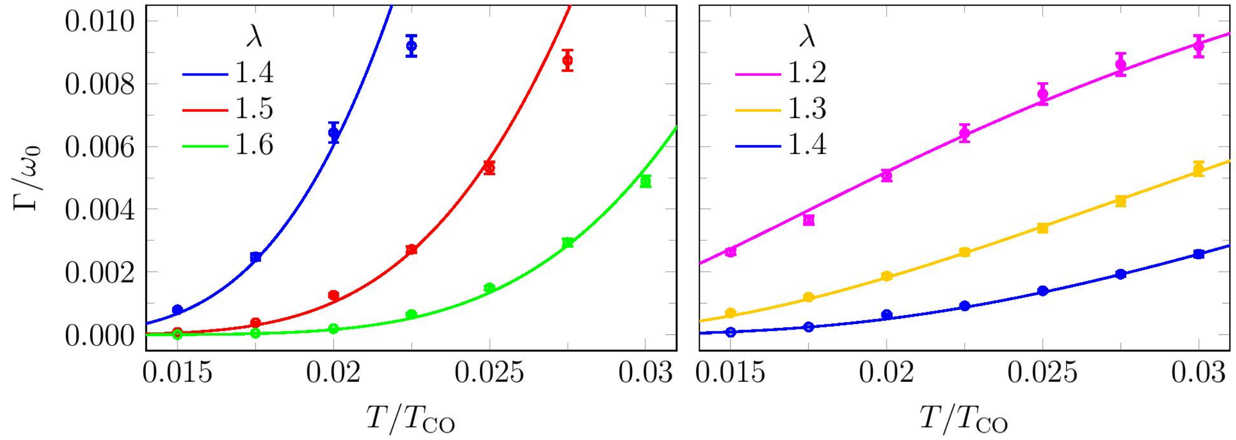
OBSERVING BUBBLES

- Theory:

$$\Gamma = A \cdot B^{0.5} e^{-B},$$

Where A is constant and $B = \dfrac{\alpha(\lambda)\epsilon}{T}$

- Left: A fitted, α taken from Gutierrez-Abed et al. (2020) [1]. Good agreement between Theory and Data.
- Right: A α fitted. Better agreement between Theory and Data.



[1] arxiv: 2006.06289

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FUTURE PLANS

- Replace time averaged potential with oscillating potential
  - Zero temperature: Instability (Braden et al., JHEP, 2018)
  - SPGPE: Can we damp this out?
- Upgrade from 1D to 2D

Full reference list: Arxiv 2006.09820

Thank you!